THE VAJONT ROCK SLIDE: NEW TECHNIQUES AND TRADITIONAL METHODS TO RE-EVALUATE THE CATASTROPHIC EVENT.
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Abstract

The Vajont landslide (9 October 1963) is one of the best known and most tragic examples of a human induced disaster. The landslide has been the object of numerous studies, not only because of its catastrophic consequences, but also because of its unexpected behaviour. Several interpretations of the event have been attempted during the last 48 years, but a comprehensive explanation of both triggering and dynamics of the phenomenon still remains elusive.

The complexity of the catastrophic 1963 landslide demonstrated the paramount importance of detailed geologic investigations. In order to reach a complete knowledge on the triggering factors of the 1963 event, a re-evaluation of the geological, geomechanical and morpho-structural features has been considered fundamental. These several features have been re-analyzed using new methods and techniques not available in the 60’s. The remote sensing techniques combined with the traditional field investigations was applied to obtain an updated, accurate and detailed geological framework. The application of different methodologies has been a key instrument for identifying the pre-existing morpho-structural and geomechanical setting that led to the failure and drove the movement direction. The information collected in order to reconstruct a 3D geological model of the landslide have been implemented in Gocad software. The results achieved to fix several significant and to date uncertain issues with respect to the landslide failure mechanism.

INTRODUCTION

The Vajont landslide (located in northern Italy) is one of the best known and most tragic examples of a natural disaster induced by a human activity. On October 9, 1963 a catastrophic landslide occurred on the northern slope of the Mount Toc when a rock mass of approximately 270 million m$^3$ collapsed into the reservoir at velocities up to 20 m/sec generating a wave that overtopped the dam and swept into the Piave valley below, causing the loss of about 2000 lives. The landslide has been object of a great number of studies, not only because of its catastrophic consequences, but also because of its unexpected behaviour. Several different interpretations of the event have been proposed during the last 48 years, but a comprehensive explanation of both the triggering and the dynamics of the phenomenon still remains unclear. In order to better understand the environmental factors that caused the 1963 movement as well as its mechanics and dynamics, the research program was focused on the accurate re-evaluation of the geological, morpho-structural and geomechanical framework and, to this end, new techniques and new methods were implemented. All the data collected were applied to develop 3D geological model as a basis for the engineering-geological model. The existing and the newly acquired data on engineering geological mapping, topography, rock mechanics, groundwater and monitoring were centralized in a GIS database to store, manage, visualize and update a large number of different data types and to reconstruct and analyze old and new landslide area scenarios.

To this purpose, detailed morpho-structural and geomechanical analyses within and outside the landslide were performed through field investigations and the application of new techniques not available in the ’60s. The increasing availability and precision of remote sensing techniques (DEM analysis, LIDAR technologies, Photogrammetric analysis, ground based and airborne LiDAR) allowed the knowledge of the geometry of the rock masses. Topographical analysis and the identification of structural features to be performed (main joint set, faults, folds, scarps, trench). Furthermore, structural and topographical information relevant to inaccessible zones of the area, were obtained so providing a complete and homogeneous distribution of the structural and geomorphological features. The accurate and detailed results achieved through the implementation of the above mentioned techniques, combined with field investigations, laboratory tests and geophysical surveys allowed to obtain a reliable 3D geological model.
REMOTE SENSING MORPHO-STRUCTURAL ANALYSIS

DEM-based analysis

The study area is characterized by a complex tectonic and morphological setting showing several and different features. The main morphological and structural features of landscape were identified using the DEM pre and post 1963 event taking into account its mesh size. In particular, a DEM-based morpho-structural analysis has been performed by Coltop 3D software (Jaboyedoff, 2004). This software displays the orientation of a pixel of a DEM using a Hue-Intensity-Saturation coding in a stereographic projection (fig.1). Thus, both the dip of the slope and its direction are coded in only one color. The methodology is largely taken from a new approach successfully tested in some previous studies (Jaboyedoff, M., Couture, R., 2004; Derron, L.H. Blokra, L., Jaboyedoff, M., 2005; Jaboyedoff et al. 2009). Using the COLTOP 3D grid data as well as point cloud data, have been represented and analyzed in 3D. It follows that the 3D surface allows firstly an easier automatic delineation of faults and main morpho-structural orientation, and, secondly, an improved structural representation that, combined with the air-photos interpretation, allowed to define the morpho-structural setting pre event. The comparison between pre and post landslide scenarios made possible to evaluate the main structural factors that led the 1963 movement.

Photogrammetry

The photogrammetric analysis was conducted thanks to the 2-year time long cooperation of the PhD student Andrea Wolter (Simon Fraser University). The photogrammetric analysis was used to provide detailed DEM of the rock slide failure surface and to add detailed structural and geomechanical information on inaccessible areas of the rock slide, on possible movement directions, and besides provided important constraints for the interpretation of the slide. To map discontinuity dips and dip directions, the AdamTech programme 3DM Analyst was used. Planes were added as circles whose centres provide discontinuity orientation information (Fig.2).

STRUCTURAL AND GEOMECHANICAL ANALYSES

The in situ survey, performed according to the ISRM standards (1978) provided a description of the main geomechanical parameters of the study area. Geomechanical measurements were performed along scan-lines on the rock outcrops (at least 3 m long). In particular, the attitudes and characteristics of approximately 1000 discontinuities were recorded on 89 stations located on the failure surface, the accumulation area and outside the landslide. The morpho-structural and geomechanical setting was
deeply investigated, in particular, discontinuity characteristics such as failure surface morphology (undulations, step-paths, rock bridges), as regards persistence, block size, roughness and intact rock properties. The rock masses characterization was also performed through the evaluation of important geomechanical parameters like GSI (Geological Strength Index) (Fig. 3), Schmidt hammer tests and point load tests. Besides laboratory test have been performed and the rock mass quality has been assessed. Remote sensing techniques provided, in general, a valuable support tool for the field investigation, because they: a) detected structural and topographical information related to inaccessible zones. b) allowed to verify and compare the structural data identified through different techniques (Remote sensing and field survey). The laboratory tests (uniaxial and triaxial tests) completed the geomechanical proprieties pattern detected. The Uniaxial Compressive Strength ($\sigma_c$), the Young’s modulus ($E_{tan}$) and the Poisson’s ratio ($\nu$) were measured on selected samples collected from outcrops located outside the landslide deposit, and from the deposit itself. The results of the analysis reflect the structural features (joint, faults, steps) affecting the slope.

Moreover, the analysis of the boreholes, drilled by RODIO company between 1964-65 on the western area of the slide, allowed to re-evaluate the stratigraphical and mechanical properties of the drilled materials and helped to reconstruct the 3D geometry of the 9 October 1963 sliding surface.

![Fig.3. Rock mass characterization using GSI values](image)

**3D GEOLOGICAL MODEL**

To date, all the slope analyses on the Vajont rockslide have involved just 2D modeling. In order to better clarify the mechanics and kinematics of the 1963 event, it was reconstructed a 3D geological model using GoCad software, which allowed to investigate structures and kinematics development of the failure surface. The input data for this model consist in: pre- and post-landslide geological maps, pre- and post-landslide digital elevation models, pre- and post-landslide orthophotos, structural data, aerial Lidar data, boreholes stratigraphy and sismicity performed. The boreholes stratigraphy and the seismic reflectors obtained by the geophysical surveys, constitute a solid constrains for the 3D model construction. Indeed they allowed to define the sliding surface depth and geometry more precisely than ever. Due to the particular behavior of the landslide - a rock slide where large coherent blocks glided along a basal slipping surface, the slide deposit is composed of some large blocks where the original stratigraphy is preserved (Fig. 3). These blocks are separated one from each other by localized discontinuities, and from the bedrock by the main sliding surface.
HYDROGEOLOGICAL ASPECTS

Though half century of scientific publications about the Vajont landslide, the correlations between the water table levels and rainfall leave still in a state of uncertainty.

The area around the M. Toc is characterized by a reduced presence of surface water and by some springs most of which characterised by small-discharge. This situation should be due to a karstic groundwater circulation. This hypothesis is a result of a direct observation, made by a hydrogeologists research group of Padova University. The upper portion of the Vajont landslide, where the main part of the meteoric waters infiltrated do not cause a significant surface flow.

SUMMARY RESULTS

The application of new methods and techniques joined to the traditional field investigation approach proves the efficacy to clarify some matter opened.

The accurate and detailed in situ field and structural and geomechanical investigations supported by remote sensing methods like DEM analysis and photogrammetric methods provided a considerable amount of data that allowed:

- To assess the importance of new techniques on rock mass quality assessment and to highlight the major factors controlling the 1963 failure mechanism.
- Realize a detailed 3D geological model and define with more certainty the sliding surface depth through the boreholes sample analysis and geophysical investigation.
- Investigate structures and kinematics development of the failure surface
- Construct the engineering geological-model that constitutes the essential start point for 2/3D numerical modeling.

References


**SUMMARY PhD ACTIVITY**

**Courses:**

**2009**

G. TEZA:”Corso introduttivo al calcolo scientifico in MATLAB”, Dipartimento di Geoscienze, Università di Padova.


A. BISTACCHI:” Modellazione geologica 3D”, Dipartimento di Geoscienze, Università di Padova

L. H. GULICK: “Corso avanzato di Inglese”, Dipartimento di Geoscienze, Università di Padova

M. FLORIS:” Introduction to GIS techniques” Dipartimento di Geoscienze, Università di Padova

G. ARTIOLI, G. DI TORO, A.M. FIORETTI. “Corso di comunicazione scientifica”, Dipartimento di Geoscienze, Università degli Studi di Padova

**2010**

A. NATALE, G. CIOTOLI “Analisi geo-spaziale in ambiente GIS”, Centro di Ricerca CERI -Valmontone (RM)


F. PESARIN, L. SALMASO “Statistica applicata alla sperimentazione scientifica”, Centro Studi per l’Ambiente Alpino - S. Vito di Cadore. March, 10-12, 2010

STURZENEGGER M. Remote sensing field course on the Hope slide, , SFU Earth Science. BC, Canada, October 2010

**Seminars**

**2009:**


**2010:**


GHIOOTTI M. M. “La frana del Vajont: rilettura dell’evento attraverso le analisi di stabilità” Padova, April, 15, 2010

FUQIANG GAO The application of brittle fracture modeling in longwall coal mining. November, 29, 2010. SFU Earth Science. BC, Canada

CARIE.ANN HANCOCK Geomorphic changes to Lillooet River due to 2010 Mount Meager landslide. December, 6, 2010. SFU Earth Science. BC, Canada

**Communications: Oral (O) Poster (P):**


SUPERCHI L., Implementation of a Geodatabase of Published and non-Published data on the Catastrophic Vaiont Landslide - Dipartimento di Geoscienze, Università di Padova (O) October 20, 2009


SUPERCHI L GENEVOIS R. La frana del Vajont. Progetto strategico d’Ateneo February 4, 2011 (O)

SUPERCHI L. WOLTER A. STEAD D. CLAGUE, J.J, M. GHIROTTI M. AND GENEVOIS R. Comparison of photogrammetric and field survey data from the sliding surface of the 1963 Vajont Slide, Italy. EGU General Assembly 2011, Geophysical Research Abstracts, Wien (Austria), May, 2-6 (P)


SUPERCHI L. Application of New Technologies for morpho-structural characterization of the Vajont Landslide Area. Geophysics and Natural Hazard. Erto 3-7 July. (O)

SUPERCHI L., MASSIRONI M. ZORZI L., GENEVOIS R. The catastrophic 1963 Vajont landslide (NE Italy) a re-evaluation: The 3D geometrical and kinematic modeling. Slope Tectonics conference 3-7 September 2011. (P)


Abstract for Conferences


Publications:


Other:

- Photogrammetry analyses support performed by A. Wolter and D. Stead May-July 2010
- Help host a visit to Padova University by Andrea Wolter, PhD student form Simon Fraser University May-July 2009
- September 15th to December 15th stay at SFU (Simon Fraser University) to discontinuity mapping (with Andrea Wolter) on AdamTech photo-models (DTM’s) of the Vajont Slide.
- Meeting with Dr. Frank Patton to discuss the Vajont landslide November 2010
- Presentation of the summarizing the results of my research to date on the Vajont slide at the Earth Science Department, Simon Fraser University, Burnaby, BC, Canada November 2010.
- Provided an introduction (with Andrea Wolter) to an undergraduate Geotechnics course laboratory session. This involved the showing of the film “VAJONT”. Dr. Frank Patton an international expert on Vajont was also present and participated in a discussion after the film.